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The Intelligent Clothing and Equipment Sizing System: Final report

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Technical Report

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Abstract

In 1996, DCIEM initiated a preliminary study to explore the feasibility of developing a low-cost automated system capable of accurately measuring and sizing individuals. The purpose of this system is to help make the distribution of clothing and equipment more cost-effective within the CF.

The development of the Intelligent Clothing and Equipment Sizing System (ICESS) has undergone three 3 phases. The first phase was an exploratory development phase focused on hardware, software architecture, and system configuration. The second phase focused on the anthropometric aspects of the systems, that is on how accurate the measurements were. In that phase, both expert anthropometrists and ICESS measured 95 females and 254 males. The third phase concentrated on the clothing sizing aspects of ICESS and the testing of traditional and non-traditional means of predicting clothing sizes from anthropometric data. This phase culminated with an assessment of the system's performance and provided the proof of concept data required to pursue implementation in the CF.

The paper summarizes work been done to date on all the three development phases. Suggestions as to its eventual implementation have also been presented.

Résumé

En 1996, l'IMCME a entrepris une étude préliminaire portant sur la faisabilité de mettre au point un système automatisé peu coûteux qui pourrait prendre les mensurations et déterminer avec exactitude la taille des personnes. Le but du système serait de permettre la distribution de vêtements et d'équipement militaire plus économiquement au sein des Forces canadiennes.

La mise au point du Système intelligent de tailles de vêtements et d'équipement (SITVE). s'est déroulée en trois étapes. La première, les études préliminaires de développement, a porté sur le matériel informatique, l'architecture logicielle et la configuration du système. La deuxième étape a surtout visé les aspects anthropométriques du système, soit le degré d'exactitude des mesures exécutées. Lors de cette étape, des experts en anthropométrie, de concert avec l'IMCME, ont pris les mensurations de 95 femmes et de 254 hommes. La troisième étape portait sur la façon dont le système déterminait la taille et les moyens classiques et novateurs de choisir des tailles de vêtements à partir de données anthropométriques. Enfin, cette étape s'est terminée avec l'évaluation de la performance du système et la cueillette des données de validation de principe permettant de justifier son utilisation dans l'ensemble des Forces canadiennes.

Le présent article résume les travaux accomplis au cours des trois étapes de la mise au point. En outre, des suggestions visant la mise en service éventuelle du système ont été formulées.

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Executive summary

In 1996, DCIEM initiated a study to explore the feasibility of developing a low-cost automated system capable of accurately measuring and sizing individuals. The purpose of this system is to help make the distribution of clothing and equipment more cost-effective within the CF.

The development of Intelligent Clothing and Equipment Sizing System (ICESS) has undergone three 3 phases. The first phase was an exploratory development phase focused on hardware, software architecture, and system configurations. This led to the decision to use a set of two digital cameras operated by a PC to take simultaneous front and side images, and to use a blue backdrop with embedded calibration markers.

The second phase focused on the anthropometric aspects of the systems, that is on the accuracy of the measurements. In that phase, both expert anthropometrists and ICESS measured 95 females and 254 males. The results of this study indicated that ICESS was indeed capable of automatically taking accurate and repeatable body measurements regardless of body shape or size.

The third phase concentrated on the clothing sizing aspects of ICESS, looking at traditional and non-traditional means of predicting clothing sizes from anthropometric data. To this end, a trial was carried out using 186 military participants. All participants were measured using ICESS and given the dress uniform size it selected. Clothing experts assessed fit and recommended changes where required. The final size was then recorded. The results showed that a success rate between 70% and 100% could be expected of ICESS, depending on the clothing item and the sizing rules used to determine the best-fitting size. This phase culminated with an assessment of the system's overall performance and provided the proof of concept required to pursue implementation in the CF.

The potential benefits of this system depend on the scope of implementation it receives. Used as a standalone system, it will provide for timesavings and a rational use of stocks. Integrated into the purchasing/manufacturing cycle, it can provide the essential ingredients for just-in-time manufacturing, or even mass customization. It is conceivable that ICESS could eventually lead to made-to-measure clothing and equipment for every individual in the CF, resulting in a reduction in inventory while providing the soldier exactly what is needed without alteration.

Meunier, P. and Yin, S. [2001]. The Intelligent Clothing and Equipment Sizing System: Final report. DCIEM TR-2001-138 Defence and Civil Institute of Environmental Medicine.

Sommaire

En 1996, l'IMCME a entrepris une étude préliminaire portant sur la faisabilité de mettre au point un système automatisé peu coûteux qui pourrait prendre les mensurations et déterminer avec exactitude la taille des personnes. Le but du système serait de permettre la distribution de vêtements et d'équipement militaire de manière plus économique au sein des Forces canadiennes.

La mise au point du Système intelligent de tailles de vêtements et d'équipement (SITVE). s'est déroulée en trois étapes. La première, les études préliminaires de développement, a porté sur le matériel informatique, l'architecture logicielle et la configuration du système. Cela a exigé l'utilisation d'appareils photos numériques commandés par ordinateur pour prendre des photos simultanées de face et de profil et d'un panneau de fond bleu doté de marques repères.

La deuxième étape a surtout visé les aspects anthropométriques du système, soit le degré d'exactitude des mesures exécutées. Lors de cette étape, des experts en anthropométrie de concert avec l'IMCME ont pris les mensurations de 95 femmes et de 254 hommes. Les résultats de cette étude ont indiqué que le SITVE pouvait réellement prendre des mensurations exactes et reproductibles quelle que soit la forme ou la taille de la personne.

La troisième étape portait sur la façon dont le système déterminait la taille et les moyens classiques et novateurs de prévoir la taille des vêtements à partir de données anthropométriques. À cette fin, un essai a été mené avec 186 militaires participants. Les mensurations de tous les participants ont été prises à l'aide du SITVE et on leur a remis la taille d'uniforme que le système avait choisi. Des experts en habillement ont évalué le degré d'ajustement et ont fait des recommandations de retouches, le cas échéant. La dimension finale a alors été consignée. Les résultats ont démontré que le taux de réussite se situait entre 70 % et 100 %, et qu'on pouvait s'attendre à ce que le système réalise ce dernier taux, selon l'article vestimentaire en cause et les règles utilisées pour déterminer la taille optimale. À la fin de cette étape, on a procédé à l'évaluation de la performance globale du système et on a fourni la validation de principe nécessaire pour passer à la mise en service du système au sein des FC.

Les avantages éventuels du système dépendent de l'étendue de la mise en service de celui-ci. S'il est utilisé comme système autonome, le système permettra de gagner du temps et d'utiliser les stocks avec rationalité. S'il est introduit dans le cycle d'achat et de fabrication, le système fournira les éléments essentiels à la fabrication juste à temps ou même à la fabrication de masse sur mesure. On peut imaginer que, grâce au SITVE, on puisse éventuellement fabriquer sur mesure les vêtements et l'équipement nécessaires à chaque membre des Forces canadiennes. Il en résultera une réduction des stocks et la possibilité de fournir à chaque soldat exactement ce dont il a besoin sans être obligé de faire des retouches.

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Introduction

In 1994, the government produced the Defence White Paper calling for reductions in resources and infrastructure and the adoption of better business practices. The Paper stated that "greater reliance will, for example, be placed on "just-in-time" delivery of common usage items to reduce inventory costs", and that improved efficiencies would come from "consolidation and the adoption of advanced technology."

The supply of clothing and equipment to the Canadian Forces (CF) has made great strides in that direction in the past few years, although there is potential to achieve even greater savings through the adoption of advanced technology. The CF supply system needs to manage a large number of operational and non-operational clothing and equipment items for its regular and reserve forces, and its objective is to make sure that sufficient quantities in each size are on hand to satisfy the demand. Meeting this objective requires detailed knowledge of the population. There are millions of dollars of stock that, if not purchased in the proper quantities, may be warehoused unnecessarily. Efficiency in the supply system, therefore, depends on an optimal balance of supply and demand.

In 1996, DCIEM initiated a preliminary study to explore the feasibility of developing a low-cost automated system for the measurement and sizing of individuals that would allow the supply of clothing and equipment to be more cost-effective in the CF. The concept was centred on an automated means of measuring and sizing individuals using digital cameras and advanced image processing techniques. Using such a system, an individual could be quickly and accurately measured. This information would be instantaneously transformed into a list of garments and their most probable size for that individual. Individual anthropometric measurements would be kept on file for later use, or could be collated to help define requirements for the purchasing of new items. This concept was called the Intelligent Clothing and Equipment Sizing System (ICESS).

The development of ICESS has undergone 3 phases of development:

1. The first phase, which started in late 1996, was essentially an exploratory development phase. Various hardware concepts and configurations were explored, and by mid 1997, the foundations of the system were laid. They included a body measurement and sizing system, and two specialized systems for measuring hands and feet. The body measurement system used two high-resolution colour digital cameras operated by a personal computer, while the hand and foot scanners used commercial flatbed scanners operated from a personal computer.

2. The second phase[1] focused on the anthropometric aspects of the systems, that is on how accurate the measurements were. This critical phase coincided with the 1997 anthropometric survey of the Canadian land forces (Chamberland et al., 1998), which was the most comprehensive ever done. Two hundred and forty three females and 465 males were measured by expert anthropometrists and imaged using the body, hand, and foot

[1] Phases two and three were partially funded by DSSPM

systems. The data collection was followed by extensive development of automatic landmarking algorithms and validation of measurements.

3. The third phase concentrated on the clothing sizing aspects of ICESS, looking at traditional and non-traditional means of predicting clothing sizes from anthropometric data. This phase culminated with an assessment of the system's performance and provided the proof of concept data required to pursue implementation in the CF.

The purpose of this report is to summarize the work that has been done to date on ICESS, and to provide suggestions as to its eventual implementation.

Body measurement and sizing

Hardware

ICESS is a PC-based system comprised of two Kodak DC120 colour digital cameras (1280 x 960 pixels) and a blue backdrop embedded with calibration markers (Figure 1). The system takes simultaneous front and side pictures of individuals standing on the imaging platform. By taking both images simultaneously, the exact posture in space is captured, and it is possible to recover the object's three-dimensional size.

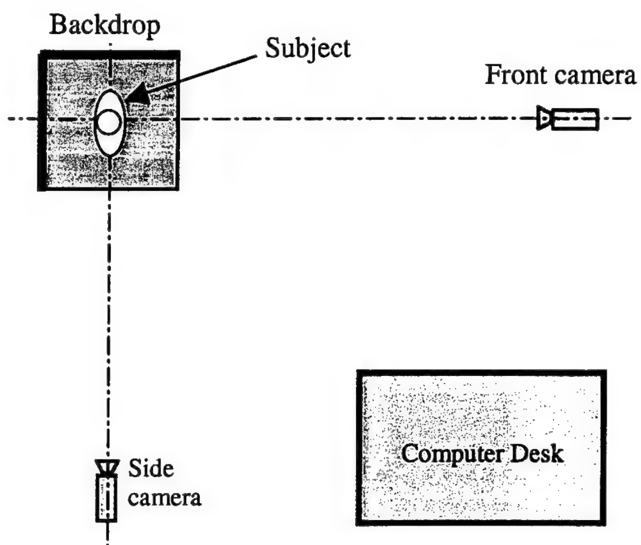

Figure 1. *Plan view of ICESS set-up.*

Operation

Set-up of the system

Set-up of the system is a relatively simple task. The DC120 camera has a built-in zoom, which enables the user to choose from a range of settings: 37 mm, 46 mm, 61 mm, 77 mm, 92 mm, 100 mm, or 111 mm. From an accuracy standpoint, the larger zoom setting is preferable because it minimizes perspective distortion. However, this means that the cameras have to be placed quite a distance away from the backdrop, which is not always possible. To date, the cameras have been used almost exclusively at the 46 mm zoom setting, which requires them to be approximately 3 metres away from the centre of the backdrop. For optimal results, the cameras should be about 1.25

metres from the floor. The camera set-up routine in ICESS is then used to fine-tune the position and orientation of the cameras. The objective is to maximize the view of the backdrop while still being able to see all of the calibration markers.

Camera calibration

Once the cameras are positioned properly, ICESS can then perform the camera calibration. Calibration enables pixel data, obtained by the camera, to be converted to millimetres. The system uses a sophisticated 3D calibration algorithm developed by Tsai (Tsai, 1986), in order to be able to compensate for perspective distortion. To this end, fifteen calibration markers were positioned on the backdrop, both in front of and behind the subject. The centres of calibration markers are located automatically by the calibration routine, and are overlaid with cross hairs as shown in Figure 2 to signal the routine's successful completion. The calibration takes about one minute to complete.

The calibration markers also fulfill an important quality assurance role. They are used as a means of detecting the inadvertent displacement of one or both of the cameras during operation. They are verified every time a picture taken, and their position is stored with the silhouette of the individuals. Thus, in the event of an accidental displacement of the cameras during operation, the system will detect it and correct the measurements accordingly. This "fallback" calibration is slightly less accurate than the original one, mainly because it uses one less marker and a slightly lower resolution image. Nevertheless, it provides an effective safeguard against what could be a significant source of measurement error.

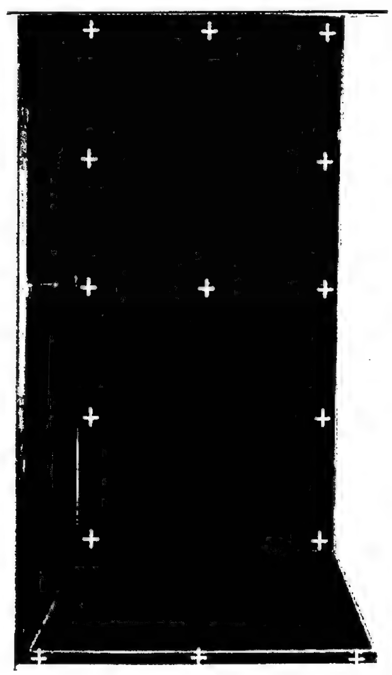

***Figure 2.** Completed camera calibration display.*

Modes of operation

ICESS has two basic modes of operation. In the first mode, the operator enters the subject's personal data and initiates the image capturing and analysis sequence. The operator instructs the subject and fulfills a quality control/troubleshooting role at the same time. This mode of operation is the most efficient and most suitable for processing large groups in a short amount of time. On the other hand, it requires dedicated personnel with appropriate training.

The second mode of operation is the self-operation mode. The self-operation mode requires the individual to understand the general process: dressing down to underwear, entering personal information, moving to the imaging platform and adopting the correct posture. One of the self-operation modes uses interactive voice control. In this version, a series of interactive voice instructions begin once the user has completed the personal instruction form. The computer guides the user through the process. For instance, it will tell the user to step onto the imaging platform and place the feet on the footprints. It will request feedback from the user to signal when this action is completed. A microphone placed on the backdrop captures this feedback. The computer will then describe the proper imaging posture, and request further feedback from the user concerning readiness to take the images. The final instructions follow the picture taking, completing the process. Although this mode of operation was relatively successful in the laboratory, noise is likely to degrade the system's performance in uncontrolled environments. For this reason, a less sophisticated but more robust alternative was developed using time delay as a means of triggering picture taking.

Self-operation will undoubtedly slow down the measurement process. Also, users will require a basic understanding of the process prior to entering the measurement booth. Instructions will need to be conveyed either textually or verbally. The time to complete the personal information form will depend on the amount of information to enter as well as the user's familiarity with computers and typing. That being said, steps could be taken to simplify the data entry procedure and reduce it to the entry of a service number. Finally, there is a lack of quality control and troubleshooting capability that comes from self-operation, and this will undoubtedly lead to subjects having to repeat the procedure from time to time. The main advantages of self-operation are that it does not require a dedicated operator and provides a more private environment for the user.

Image acquisition and processing

Regardless of the mode of operation chosen, the system needs to know the gender of the user, since the landmarking algorithms differ, and the service branch, to determine the type of uniform required. The current list of personal information includes service branch, service number, name, rank, gender and weight. Weight information is not required for garment sizing, but it is, along with stature, an excellent anthropometric indicator. Personal information is entered using the ICESS graphical user interface. The individuals then proceed to the platform where they are required to place their

feet on the footprints. The front and side images are acquired and downloaded at the click of a button. The individuals are free to leave the platform after the pictures are taken.

The image analysis starts once the pictures are downloaded. The automated process, which is illustrated in Figure 3, includes pre-processing of the images, verification of the calibration markers, separation of the body image from the background (segmentation), tracing of the silhouette, location of the landmarks, calculation of the anthropometric variables, and selection of the most probable garment size.

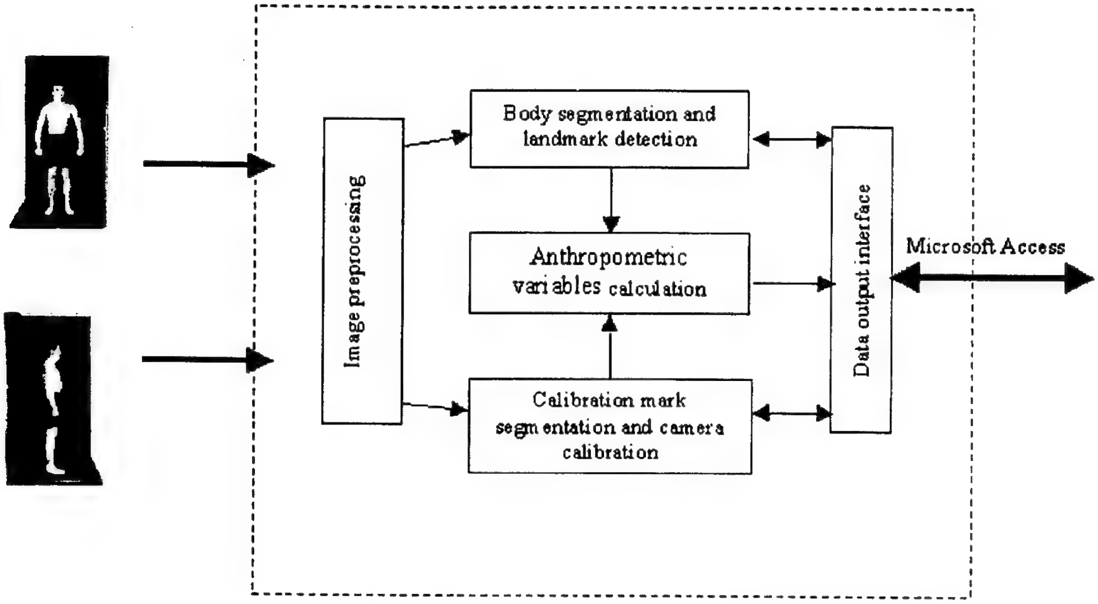

Figure 3. *Image analysis process.*

Figure 4 shows the ICESS interface at the end of the process. The interface has three panes. The first pane shows the completed personal information form along with the individual's anthropometric measurements. The other two panes show the processed front and side images, and provide visual feedback on the proper operation of the system. Segmentation and landmarking errors can be detected in these views. Although this was an essential feature during the development of the system, the display of the images is not a necessity. Thus, instead of seeing the silhouette, landmarks and picture, the implemented system would only display the silhouette and landmarks.

Although the automatic landmarking algorithm is very reliable, there are times when landmarks may be misplaced. The software was designed to deal with these relatively rare occasions by enabling the operator to drag and drop the misplaced landmark to its proper place after the fact. The affected dimensions are automatically recalculated.

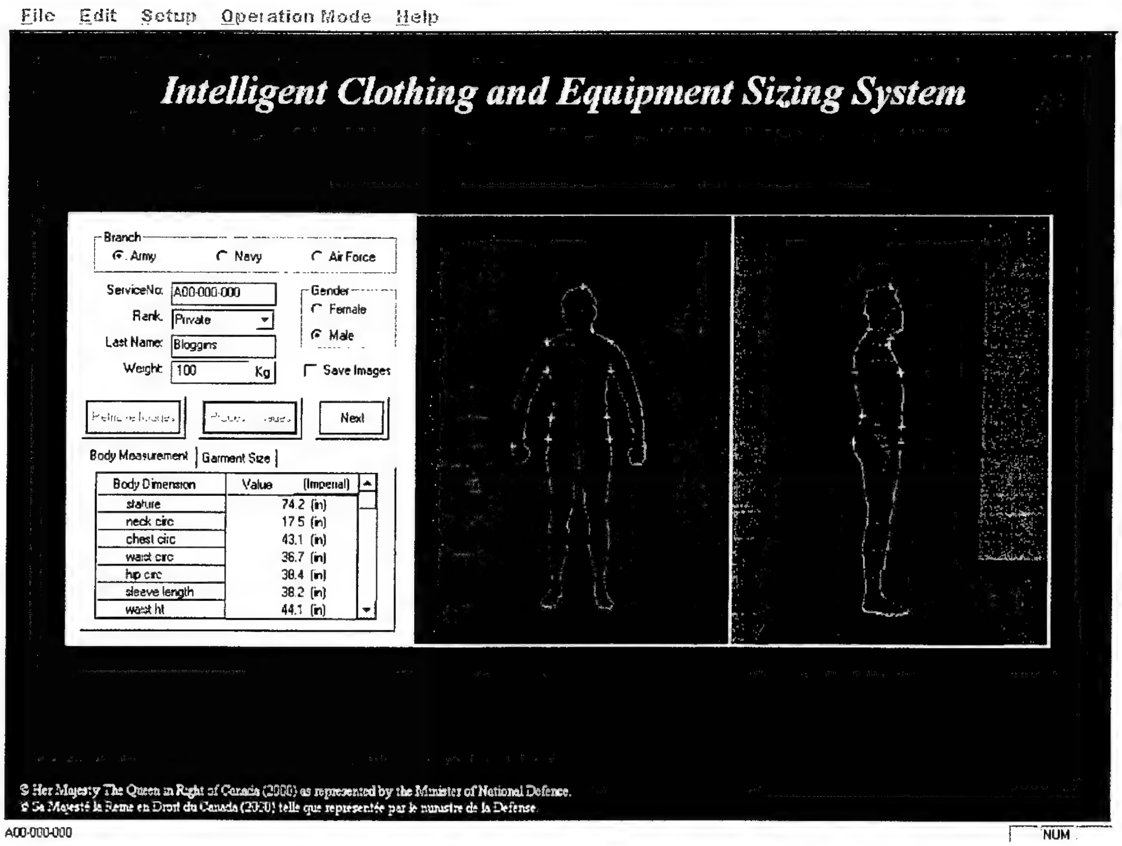

Figure 4. *Processed image showing silhouette, landmarks and anthropometric measurements.*

Automatic landmarking

The accuracy of the measurements made by ICESS depends on landmark identification. The algorithms developed for ICESS have proven to be reliable regardless of body shape while being directly applicable to clothing and equipment sizing. This is one of the prime accomplishments of this system. Some of the landmark definitions were based on well-established criteria or standards, while others had to be developed to ensure relevance to clothing sizing. Chest circumference, for instance, was based on the standard definition while waist circumference required a non-standard definition.

ICESS is capable of finding landmarks for a large number of anthropometric variables. However, for clothing and equipment sizing they were limited to the following 27, as illustrated in Figure 5:

1. top of the head (2 landmarks (front and side));

2. neck (4 landmarks);

3. acromion (2 landmarks);

4. chest (4 landmarks);
5. waist (4 landmarks);
6. hip (4 landmarks);
7. crotch (1 landmark);
8. thighs (4 landmarks); and
9. wrists (2 landmarks).

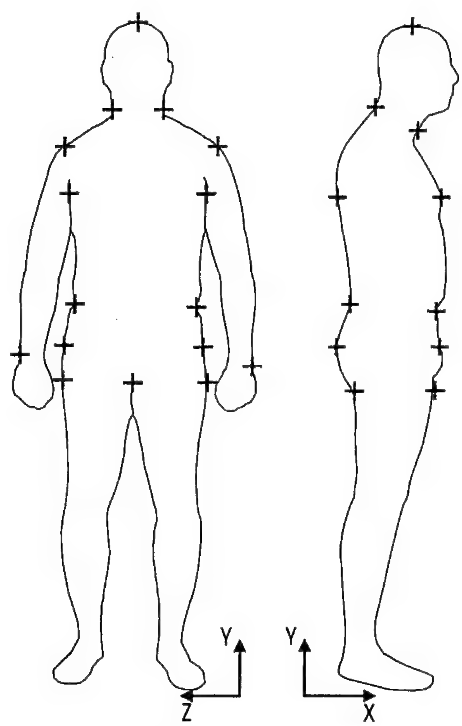

Figure 5. *ICESS landmarks.*

Measurements

From the 27 landmarks listed in the previous section, ICESS extracts 38 traditional measurements (see Table 1). The term traditional refers to measurements taken with anthropometers and tapes. ICESS makes two types of measurements that can be called direct and indirect measurements respectively. Direct measurements convert pixel data to millimetres using the camera calibration parameters. Essentially, anything that can be extracted from a single view (front or side) is a direct measurement. This includes heights, lengths, breadths, depths, contours, etc. Indirect measurements need to be derived or extrapolated from direct measurements. All of the circumferences fall in this category.

In addition to traditional measurements, ICESS is also capable of extracting 3D landmark information from the front and side images. Use of 3D landmark data has been shown to improve clothing sizing performance (Meunier, 2000). Table 2 lists the landmarks for which x, y, z data are extracted.

Table 1. *List of measurements*

	Dimension		Dimension
1	Stature	20	Chest circumference below breast
2	Neck breadth, natural	21	Waist breadth, natural
3	Neck depth, natural	22	Waist depth, natural
4	Neck height, natural	23	Waist circumference, natural
5	Neck circumference, natural	24	Waist breadth, trousers
6	Neck breadth at base	25	Waist depth, trousers
7	Neck depth at base	26	Waist circumference, trousers
8	Neck height at base from back	27	Waist height, back
9	Neck circumference at base	28	Waist height, front
10	Acromial height, left	29	Waist angle
11	Acromial height, right	30	Hip breadth
12	Biacromial breadth	31	Hip depth
13	Sleeve outseam	32	Hip circumference
15	Sleeve length, left	33	Crotch height
16	Sleeve length, right	34	Thigh breadth
17	Chest breadth	35	Thigh depth
18	Chest depth	36	Thigh circumference
19	Chest circumference	37	Strap length (for backpack)
20	Chest circumference below breast	38	Back length (for backpack)

Table 2. 3D landmarks provided in ICESS

	Landmark Name	Field names in Database
1	Stature	StatX, StatY, StatZ
2	Neck front	NeckNFX, NeckNFY, NeckNFZ
3	Neck back	NeckNBX, NeckNBY, NeckNBZ
4	Neck left	NeckNLX, NeckNLY NeckNLZ
5	Neck right	NeckNRX, NeckNRY,NeckNRZ
6	Neck base, front	NeckBFX, NeckBFY, NeckBFZ
7	Neck base, back	NeckBBX, NeckBBY, NeckBBZ
8	Neck base, left	NeckBLX, NeckBLY, NeckBLZ
9	Neck base, right	NeckBRX, NeckBRY, NeckBRZ
10	Left acromion	AcrLX, AcrLY, AcrLZ
11	Right acromion	AcrRX, AcrRY, AcrRZ
12	Chest, front	ChestFX, ChestFY, ChestFZ
13	Chest, back	ChestBX, ChestBY, ChestBZ
14	Chest, left	ChestLX, ChestLY, ChestLZ
15	Chest, right	ChestRX, ChestRY, ChestRZ
16	Natural waist, front	WaistNFX, WaistNFY, waistNFZ
17	Natural waist, back	WaistNBX, WaistNBY, waistNBZ
18	Natural waist, left	WaistNLX, WaistNLY, waistNLZ
19	Natural waist, right	WaistNRX, WaistNRY, waistNRZ
20	Waist front, trousers	WaistFX, WaistFY, waistFZ
21	Waist back, trousers	WaistBX, WaistBY, waistBZ
22	Waist left, trousers	WaistLX, WaistLY, waistLZ
23	Waist right, trousers	WaistRX, WaistRY, waistRZ
24	Wrist, left	WrLX, WrLY, WrLZ
25	Wrist, right	WrRX, WrRY, WrRZ

Data storage

ICESS stores two types of data: tables of anthropometric data and clothing sizes, and the graphical data of the silhouette and landmarks. ICESS stores the numeric data in a Microsoft Access database file, and graphical data in its own binary format. The file was given the extension ".ice". An example of a retrieved .ice file is shown in Figure 6.

The .ice file contains essential body shape and size information in the form of a silhouette and its associated landmarks. It is a useful diagnostic tool that can be used to identify misplaced landmarks or poorly segmented images. Misplaced landmarks can be corrected interactively without requiring the individual to be re-imaged, whereas poorly segmented images would require reprocessing. Because the .ice files are stored, they can be re-processed if and when new anthropometric measurements are required or when new garments are introduced in the supply system. Thus, new dimensions and garment sizes can be generated without the presence of the individuals, saving time and effort.

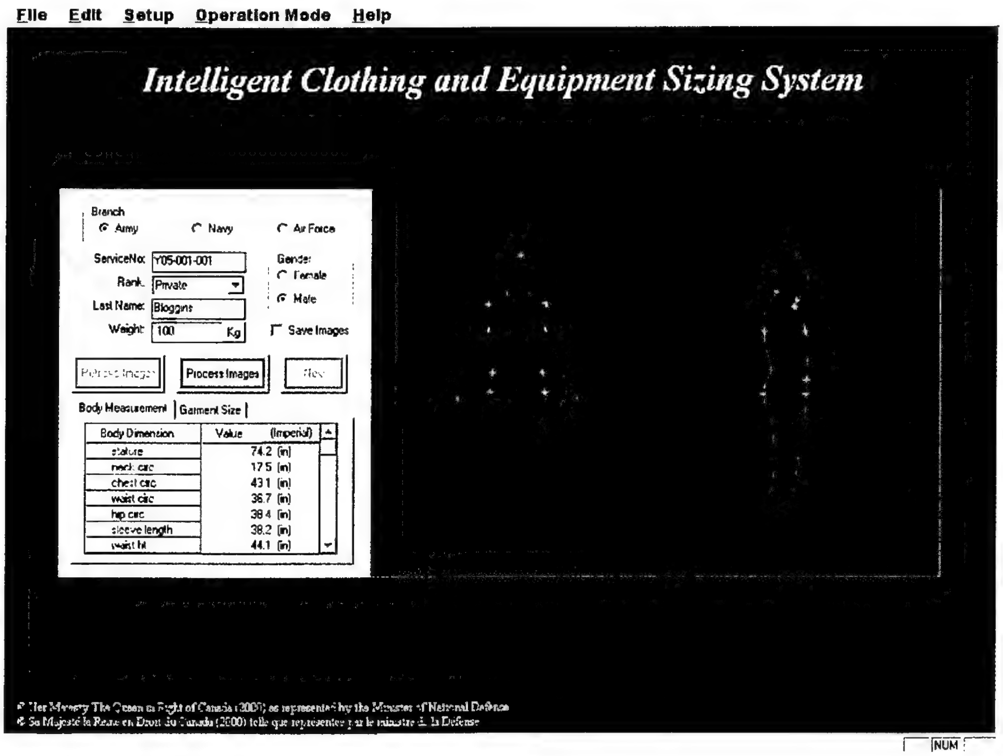

__Figure 6.__ Retrieved .ice file.

Clothing and equipment sizing and printout

Clothing sizes are calculated immediately after the anthropometric measurements are made. ICESS determines the most probable clothing and equipment size for that individual based on the relevant dimensions.

The final stage of the process involves transferring the clothing sizing information to store personnel. This can be done through the use of hardcopies or electronic means, depending on the type of arrangement required. In its current form, ICESS generates a summary printout that includes personal information, the silhouette with its landmarks, anthropometric measurements, as well as the size calculated for various clothing and equipment items. A sample printout sheet is shown in Figure 7 with sizes for the Air Force hot wet garment, the Army service dress uniform, and the new backpack.

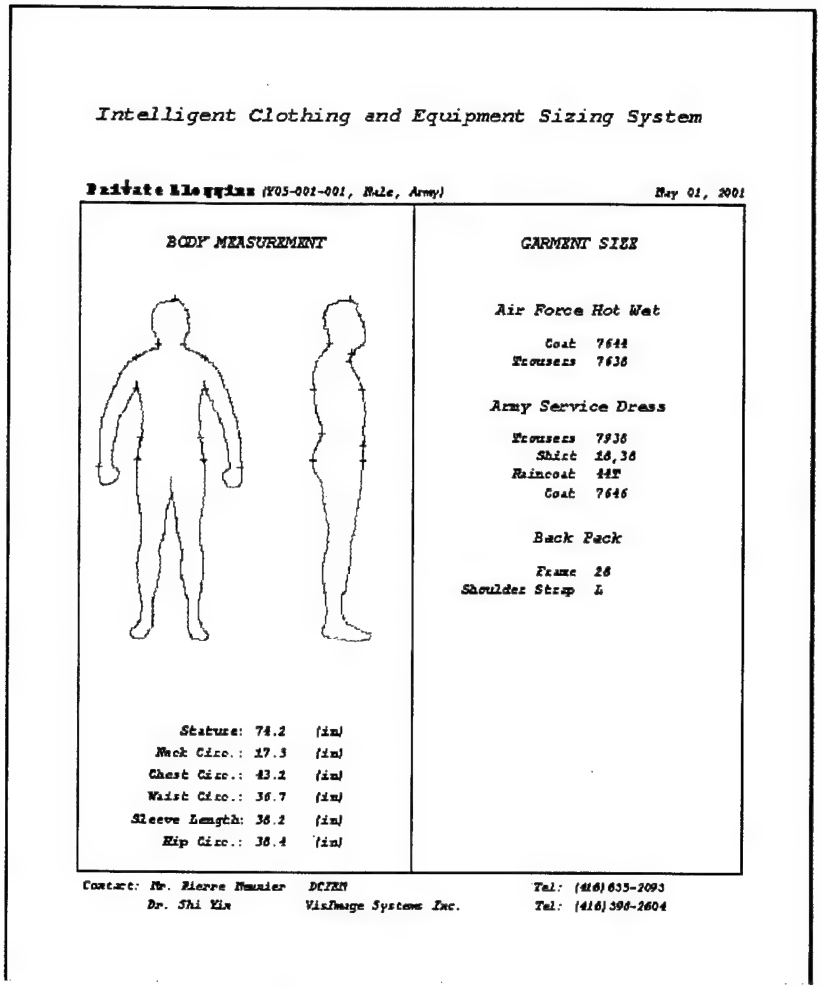

Figure 7. *Printout sheet.*

Processing capacity

The maximum processing rate can be viewed as a theoretical limit, that is one that can only be achieved under ideal conditions. Timing of the various stages of the process was done with the system's Pentium II computer (300 MHz). This assessment showed that a maximum processing time of about 55 seconds per individual is possible. This rate includes entry of the service number as well as the acquisition, downloading, and processing of the images, as shown in Figure 8, and corresponds to a capacity of about 65 individuals per hour.

The hardware used in ICESS (Pentium II, DC120) is now considered old technology. As Figure 8 illustrates, great gains can be obtained through the use of newer technology. For instance, a Pentium IV computer could reduce the overall processing time by 17 seconds or so. This equates to a throughput of about 95 individuals per hour. A further decrease in processing time could be achieved by using cameras equipped with FireWire (IEEE 1394) or USB2.0 connections. Using FireWire technology would result in an overall processing time of 11 seconds or so, increasing the maximum throughput to over 300 individuals per hour.

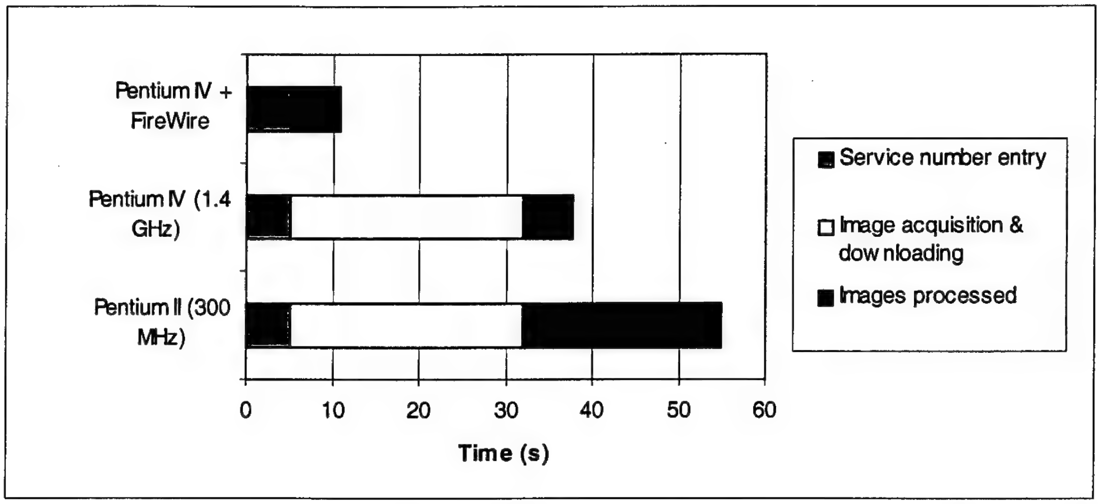

Figure 8. *Processing timeline.*

Since the self-operation mode has not yet been tested outside of the lab, it is difficult to estimate what this mode can achieve in terms of throughput. One of the main issues with this mode will be to ensure the individuals know what is expected of them before entering the measurement booth. They need to know about the need to complete the personal information form, to step on the measurement platform, to adopt the required posture (making sure the arms are along the body), to stand still for the cameras, and to pick up the printout. It is anticipated that this process could take as little as 4 to 6 minutes to complete, representing a rate of 10 to 15 individuals per hour.

Measurement performance

In spite of highly standardised protocols designed to maximize the degree of repeatability and accuracy of measurements, anthropometric data are not always as reliable as they appear. Many factors come into play during the measurement of human subjects, which can result in the appearance of numerous sources of error. Some of the important sources include posture, identification of landmarks, instrument position and orientation, and pressure exerted by the measuring instrument (Davenport et al., 1935). The difficulty in controlling all potential sources of error is such that it has been said that true values are seldom measured in anthropometry (Jamison and Zegura, 1974).

The accuracy and precision of anthropometric measurements are at the mercy of the measurers. Even if measured by highly trained observers, comparison of two populations may be meaningless (Bennett and Osborne, 1986). In a comparative study by Kemper and Pieters, 1974, fifty boys were measured independently by experienced observers in two institutes. Both teams of observers were trained to the same measurement techniques and used the same measuring instruments. In spite of this, systematic differences were found in nine of the twelve measurements taken. Pearson correlations between 0.872 (biacromial diameter) and 0.996 (stature) were found between the measurements taken by the two groups. Although the variable with the lowest correlation (biacromial diameter) did not present

systematic errors, it suffered from repeatability problems (precision error). The results of these and many more studies show how difficult it is to measure humans, even under controlled conditions and after extensive training of the observers.

In light of this, it is difficult to expect DND supply technicians to meet standards that trained anthropometrists seem hard pressed to meet. Therein lies one of the important advantages of an intelligent automated system: computerized image-based system can provide uniformity of measurement and clothing sizing criteria across the Canadian Forces, regardless of who operates it. However, although ICESS can overcome some of the problems of traditional anthropometry, it cannot overcome all sources of error. It is important to know the limitations of the instrument and not assume infallibility of the results. Image-based systems are prone to perspective distortion, camera resolution, landmarking error, and modelling error (since circumferences are not measured directly).

The error of a measurement is defined as the difference between the measured value and the true value of the item being measured and is made up of two components. Errors can be catalogued as either random (precision error) or systematic (bias error). *Accuracy* is the difference between the measured and true values, whereas *precision* is defined as the difference in values obtained when measuring the same object repeatedly. The following is a summary of work that was done to quantify both aspects of ICESS measurements (Meunier and Yin, 2000). The results were compared with those of highly trained anthropometrists, and put in perspective in the context of clothing and equipment sizing.

Measurement accuracy

The accuracy of ICESS was assessed by comparing its measurements against those collected traditionally in the 1997 survey of the Canadian Land Forces (Chamberland et al., 1998). Six dimensions were selected as a basis for comparison because of their relevance to clothing sizing. These were: stature, neck circumference, chest circumference, hip circumference, and sleeve length (spine-wrist). Waist circumference was excluded from this comparison due to the difference in measurement definitions.

The test sample consisted of a subset of 349 subjects (95 females and 254 males) from the survey that had been measured both with traditional methods and with ICESS. The image capture was performed within 90 minutes of the traditional measurements to avoid the effects of daily body variations. The results are shown in Table 3.

Table 3. Comparison of ICESS with traditional measurements

Measurement	Females			Males		
	Mean	Std.Dev.	Corr.	Mean	Std.Dev.	Corr.
Stature:						
Manual	1632	61	0.98	1748	64	0.99
ICESS	1632	62		1748	65	
Neck circumference:						
Manual	329	18	0.88	395	23	0.94
ICESS	329	16		395	22	
Chest circumference:						
Manual	956	87	0.95	1024	83	0.94
ICESS	957	84		1024	78	
Hip circumference:						
Manual	1027	91	0.98	1005	72	0.94
ICESS	1026	89		1004	68	
Sleeve length:						
Manual	799	34	0.79	876	35	0.76
ICESS	800	27		875	26	

Based on t-tests, no significant difference was found between both types of measurement, indicating that that on average, ICESS measurements are comparable to traditional measurements taken by trained anthropometrists. Correlations ranged from 0.79 for sleeve length to 0.99 for stature, reflecting a close correspondence between the two sets of data. Sleeve length was found to be the least reliable measurement, as evidenced by the spread of results. The standard deviation of traditional measurements was 34 mm compared to 27 mm for ICESS. This is evidence of the difference in measurement definitions, where the posture adopted for ICESS is significantly different to that required for traditional measurements. Review of the survey images also revealed the presence of inconsistent hand postures (some in pronation, some in supination), arms that were not vertical, and bent elbows. More recent trials have shown that better control of the imaging posture will improve the reliability of this measurement considerably. Nevertheless, further validation of this measurement may be required if it is determined that greater accuracy is required for clothing sizing.

Precision of measurements

The precision of ICESS was determined by performing two sets of repeated measurements (10): one on a full size plastic mannequin, and one on a human subject. The plastic mannequin was used as a means of testing the intrinsic precision of

ICESS, to test the performance of the automatic landmarking, segmentation, and measurement. In some ways, this represents the optimal performance conditions, and can be viewed as a benchmark. The second set of measurements was performed using a live subject, who was instructed to move away from the platform between measurements. Thus, these repeatability results include variability due to breathing and differences in posture in additional to ICESS' intrinsic variability.

Figure 9 shows the values within which 95% of the repeated measurements (1.96 * SD) would fall relative to the mean. For instance, 95% of the mannequin's stature measurements should fall within two millimetres of the mean if repeated measurements were to be made. Examination of Figure 9 indicates that, as expected, the mannequin's repeated measurements were less variable than those of the human. However, the human results were within two or three millimetres of the "ideal" for most measurements. The exceptions were for sleeve length, waist and chest circumferences, the latter two being influenced by breathing and posture. Hinges at the shoulder, elbow and wrist hindered the repeatability of the sleeve length measurements of the mannequin.

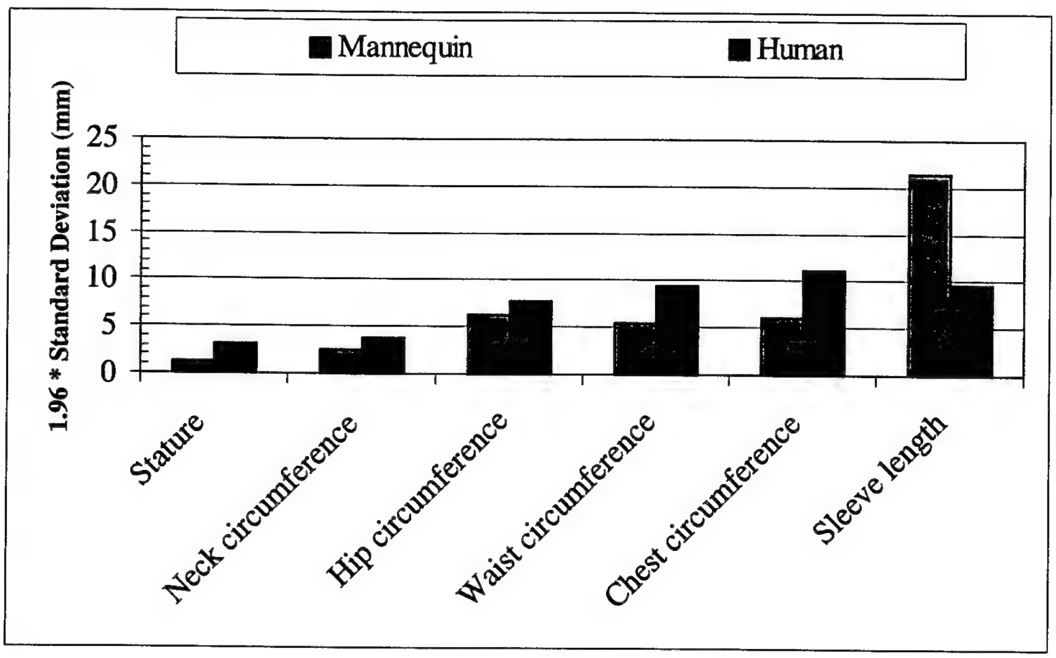

Figure 9. *Repeatability of ICESS measurements on a mannequin and human.*

Computer versus human repeatability

The results of the repeatability study were compared with those of two recent large-scale surveys where accuracy and precision were monitored throughout. The first survey was conducted on the Canadian Land Forces personnel in 1997 (Chamberland et al., 1998), and the second was conducted on US Army personnel in 1988 (Gordon

et al., 1989). Repeated measurements were an integral part of both surveys, but the methodology was slightly different. In the Canadian Land Forces survey, subjects were re-measured by the same observer within minutes (10 to 90 minutes) of the first measurement (see Forest et al., 1999 for details). This can be viewed as the best-case scenario in terms of repeatability, since it is assumed that the same observer will measure in the same way using the same landmarks. In the US Army survey, subjects were also re-measured within minutes but this time by a second observer. This case can be viewed as the best-case scenario for repeatability by two highly trained observers.

The technical error of measurement (TEM) was used as the basis for the comparison. TEM is essentially a form of standard deviation and is calculated as follows (Malina et al., 1973):

$$r = \sqrt{\frac{\sum_{i=1}^{n}\left(\sum_{j=1}^{k} x_j^2 - \frac{1}{k}\left(\sum_{j=1}^{k} x_j\right)^2\right)_i}{n(k-1)}} \quad (1)$$

where x_j is the j[th] replicate of the measurement, k is the number of replicates, and n is the number of subjects.

The TEM is expressed in the units of measurement, and is interpreted in the same manner as a standard deviation, that is: two thirds of the measurements should fall between $\pm r$ of the mean of repeated measurements. The TEM is sometimes used to compare values taken by measurers with those of a trained anthropometrist. A low r-value indicates high precision on the part of the measurer.

Using the human repeatability data, the technical error of measurement of ICESS was compared to the corresponding values obtained by a single trained observer (Forest et al., 1999) and those obtained by two trained observers (Gordon and Bradtmiller, 1992)). The results are shown in Figure 10.

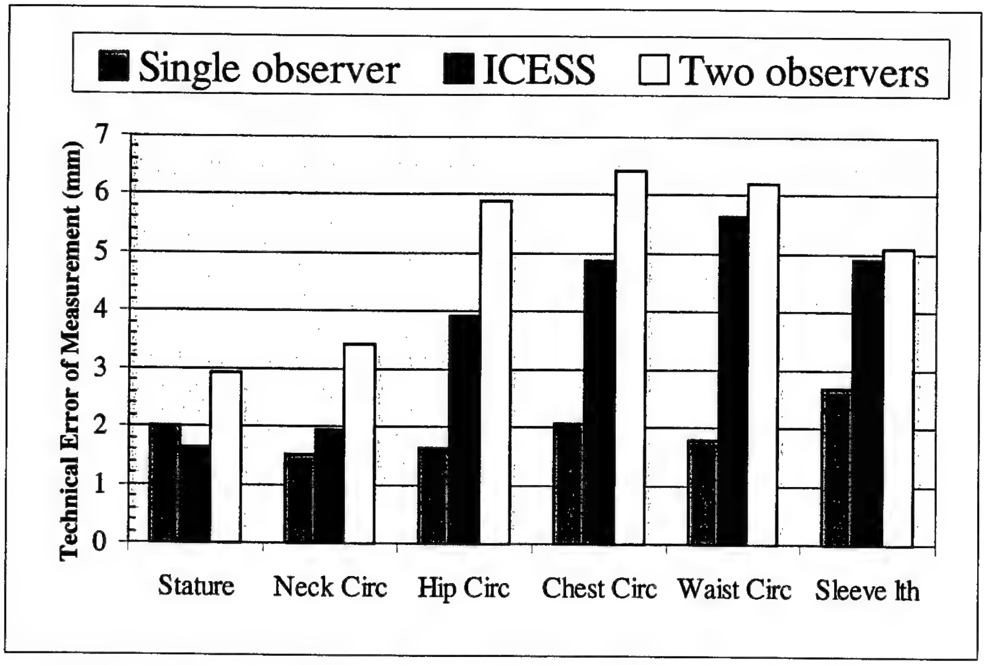

Figure 10. *Repeatability of ICESS measurements on a mannequin and human.*

Although the computer measurements contain an additional source of error due to automatic landmarking, the results of ICESS are generally between single and dual observer TEMs. This indicates that ICESS measurements are more precise than those of two trained observers but somewhat less than those of a single observer.

Required accuracy

It is important to remember that the ultimate goal of ICESS is to determine the best fitting size of garment for a given individual rather than providing the most accurate body measurements. Because it is possible to make a reliable link between the body and the garment size by simply having a consistent way of extracting measurements, the emphasis should not be on accuracy but rather on the reliability of measurements.

A number of factors affecting garment fit were analysed in the context of measurement accuracy and precision to determine areas requiring special attention. These factors can be grouped into two categories: one pertaining to how garments are designed and manufactured, and the other pertaining to the body's variation over time.

Garment related factors

Some of the factors that can impact the requirement for accuracy and precision are:

- Garment design or cut. The criticality of measurements will depend on whether a tight fitting or loose fitting garment is to be fitted. A loose fitting garment will not require highly accurate measurements, whereas a close fitting one will.

- Manufacturing tolerances. Maintaining tight manufacturing tolerances on clothing items can be both difficult and costly. As a result, manufacturers need to achieve a satisfactory trade-off between fit of the clientele and cost of the garment. The tolerances used could be interpreted as the amount of fluctuation in garment dimensions having minimal impact on fit, and as such could be viewed as an indicator of the importance of measuring the associated dimensions accurately and precisely. Table 4 shows some typical manufacturing tolerances for trousers and shirts in DND. Using this reasoning, one can conclude that neck measurement requires the highest degree of accuracy and precision.

Table 4. *Typical manufacturing tolerances*

Garment	*Variable*	*Tolerance (mm)*
Trouser	Waist	± 13
	Inseam	± 13
Shirt	Neck	± 3
	Chest	± 13
	Sleeve	± 13

- Clothing size increments. Clothing size increments can also be viewed as indicators of the criticality of some of the body measurements and of the importance given to fit. For instance, clothing items that only require three sizes will either be very adjustable/accommodating or very loose fitting. Consequently, accurate measurement of the body will not be a critical requirement. Clothing items that require 40 sizes, such as in the case of dress shirts, reflect the need to achieve good fit. Typical size increments for DND dress uniforms are shown in Table 5.

Table 5. *Typical clothing size increments for dress uniforms (mm)*

Garment	*Variable*	*Size increments (mm)*
Trousers	Stature	76
	Waist	51
Shirt	Neck	13
	Sleeve length	51
Jacket	Stature	76
	Chest	51

Thus, it is clear that while a high degree of accuracy and precision in anthropometric measurements is desirable, it is not always necessary. The requirements need to be balanced against the ease[2] provided in the garment, the magnitude of manufacturing tolerances, number of sizes, etc. In that context, it is clear that, by far, the greatest degree of accuracy is required for neck measurement.

Body related factors

It is important to remember that it is impossible to assign highly accurate measurements to the human. The human body changes with movement, with breathing, with time, etc. Several body dimensions can change substantially over short periods of time and yet the clothing still appears to accommodate it.

The magnitude of variations of body measurements over time was studied by Davenport et al., 1935. In those experiments, repeated measurements of one subject were made at various times of day, and over a number of days, by the same observer. The results, which are shown in Table 6, show that the measurements can vary quite significantly. It was found, for instance, that 95% (1.96 * standard deviation) of waist circumference measurements taken over time could fluctuate within ± 21 mm of the mean. One could wonder about the practical utility of measuring this moving target with millimetre accuracy.

Table 6. *Body variation over several days (Davenport et al., 1935)*

	1.96* s.d. (mm)
Waist circumference	± 21
Chest circumference	± 15
Neck circumference	± 5

The purpose of the foregoing discussion was to point out some of the sources of variability extrinsic to the measurement process in order to put the requirements for accuracy and precision into perspective. It is argued that the anthropometric performance requirements need to be balanced against a number of factors, including short-term body variations. Perhaps it is not a coincidence that the data found in Table 4 and Table 6 are in agreement. In a balanced approach, measurement accuracy should be consistent with both.

[2] Looseness

Sizing performance

While the ability to make accurate and repeatable anthropometric measurements can be important in some cases, measurements alone are not sufficient to determine the optimal clothing size for a given individual. A link must be established between body size and the clothing sizing system. This mapping, which is usually obtained or validated through fitting trials, involves knowledge of the critical variables for the particular garment and of the critical sizing values, that is the values at which the clothing size changes.

Conventional methods of linking body measurements to clothing size in the CF use two or three key dimensions to determine clothing size. Stature and waist circumference may be used to determine trouser size, neck circumference and sleeve length for shirts, etc. This method has the advantage of being simple and easy to use: a look-up table is all that is needed to select clothing sizes. However, it can be somewhat limiting in the context of a computer sizing application, where complex logic and arithmetic calculations can be made in a fraction of a second. Because of this, two distinct approaches were explored during the development of ICESS: the conventional approach, and a multivariate approach.

A trial was carried out in 1999 to assess the ability of ICESS to correctly predict clothing size (Meunier et al., 1999). In all, 186 military participants took part in the trial: 39 females and 147 males. The trial focused on sizing of the dress uniform, which includes the long sleeve shirt, the jacket and the trousers. A complete set of dress uniform sizes were available for this purpose. This included 40 sizes of shirt, 44 sizes of jacket, and 46 sizes of trousers for males, and 37 sizes of shirt, 27 sizes of jacket, and 27 sizes of slacks for females. Each subject was given the clothing size predicted by ICESS. These were assessed by the participants themselves as well as by clothing experts.

Figure 11 compares the successful size prediction rate obtained from conventional and multivariate sizing rules. The multivariate sizing rules were derived using discriminant function analysis. Because this type of analysis represents an optimized solution, the conventional rules were revisited and optimized as well to permit a fair comparison. Also, the multivariate rules were not limited to lengths and circumferences, but also considered 3D landmark coordinates, which were shown to improve size prediction (Meunier, 2000).

It is clear from Figure 11 that the multivariate approach can improve the overall size prediction success rate of ICESS. Modest but consistent increases in prediction rate (2% to 5%) were noted for all garment types, and in particular for shirts, where a substantial increase (14%) was observed. This improvement was attributed to the use of 3D landmark coordinates, which are thought to provide a better characterization of shape than single circumference measures, leading to a better classification of cases.

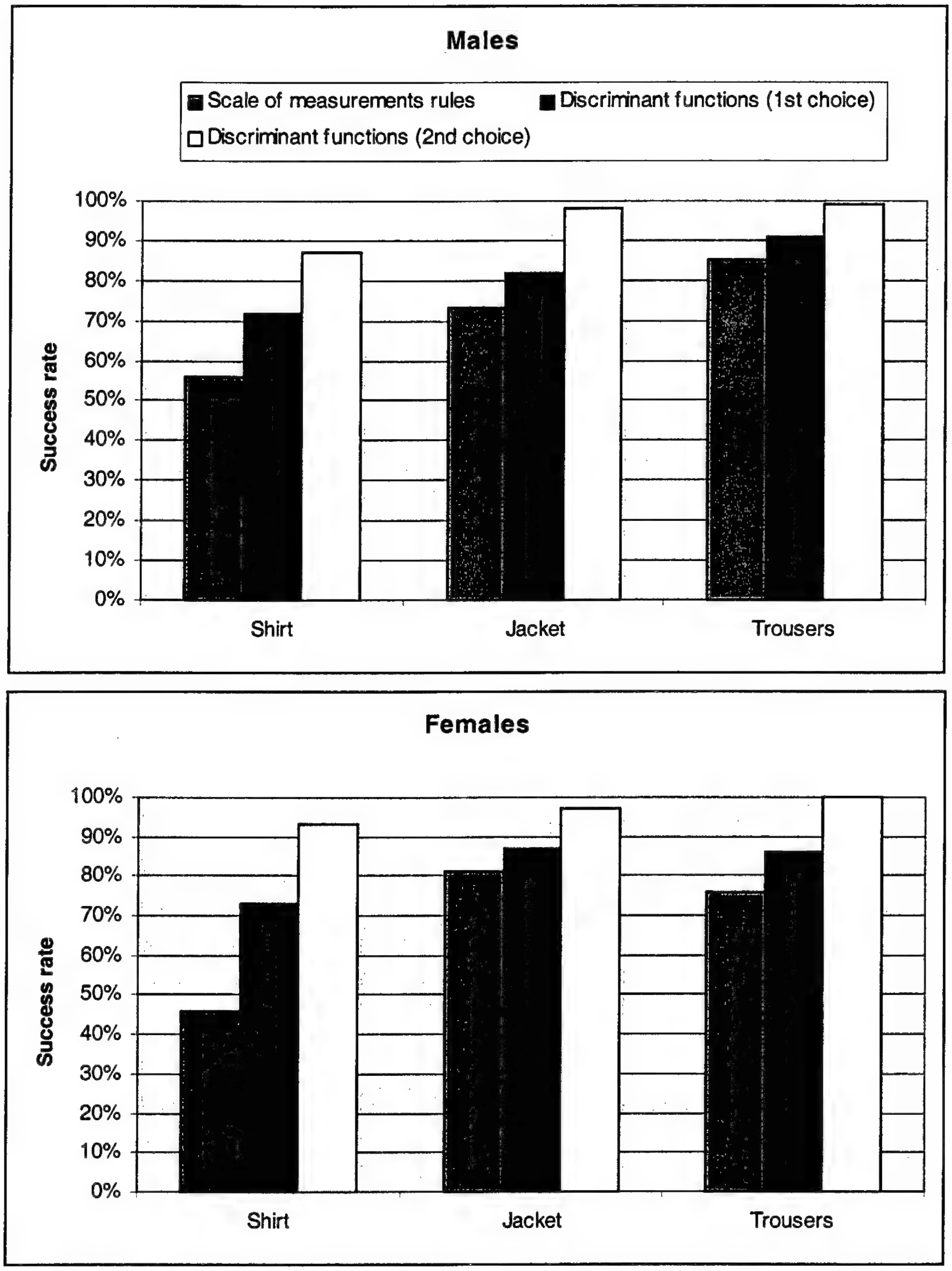

Figure 11. *Comparison of clothing sizing rule performance for males and females.*

Discriminant functions were found to have a further advantage over conventional sizing methods, in that they take into account as many anthropometric variables as necessary to predict clothing size, whereas conventional methods use only one or two. Also, this statistical technique lends itself to predicting not only the most likely clothing size, but also the second

most likely, third most likely, and so on. It can identify whether the choice of size was clear-cut, in which case there would be a high degree of confidence in the size selection, or whether it was borderline. Borderline cases would be offered the choice of two garment sizes to try, rather than one. This could be a very useful feature, as the clothing sizing trial data indicated that in most cases, incorrect size predictions occurred when the values of two discriminant functions were very close to each other. By using this strategy, success rates approaching 100% could be attained.

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Hand and foot measurement and sizing

Since the whole body imaging system was not considered adequate for hand and foot measurement, specialized systems were developed. The following is a description of the work done.

Hardware

Both the hand and foot measurement and sizing systems were developed starting in 1996, using a low cost flatbed scanner made by Microtek. Microtek's ScanMaker E3Plus was used. The scanner's glass was replaced with a thicker sheet of tempered glass for the purpose of foot scanning during the 1997 survey of the land forces. The scanner was controlled by a personal computer by way of an interface similar to that of the body scanner.

Measurements

The mode of operation requires individuals to place their hand on the glass, or stand on the thick tempered glass, while the scanner acquires the image. The software then processes the image and traces a contour of the hand or foot. The appropriate landmarks are automatically detected, and measurement is made of the key features. From those measurements, the appropriate size of hand wear or footwear is selected. Processed images of the hand and foot are shown in Figure 12.

The hand algorithms currently measure all five digit lengths, palm breadth, and digit 3 breadth. The foot algorithms measure foot length and breadth, heel breadth, heel to ball of foot length, inner and outer plantar arch lengths, ball of foot flex angle, and anterior and posterior flexion angles, as shown in Figure 13.

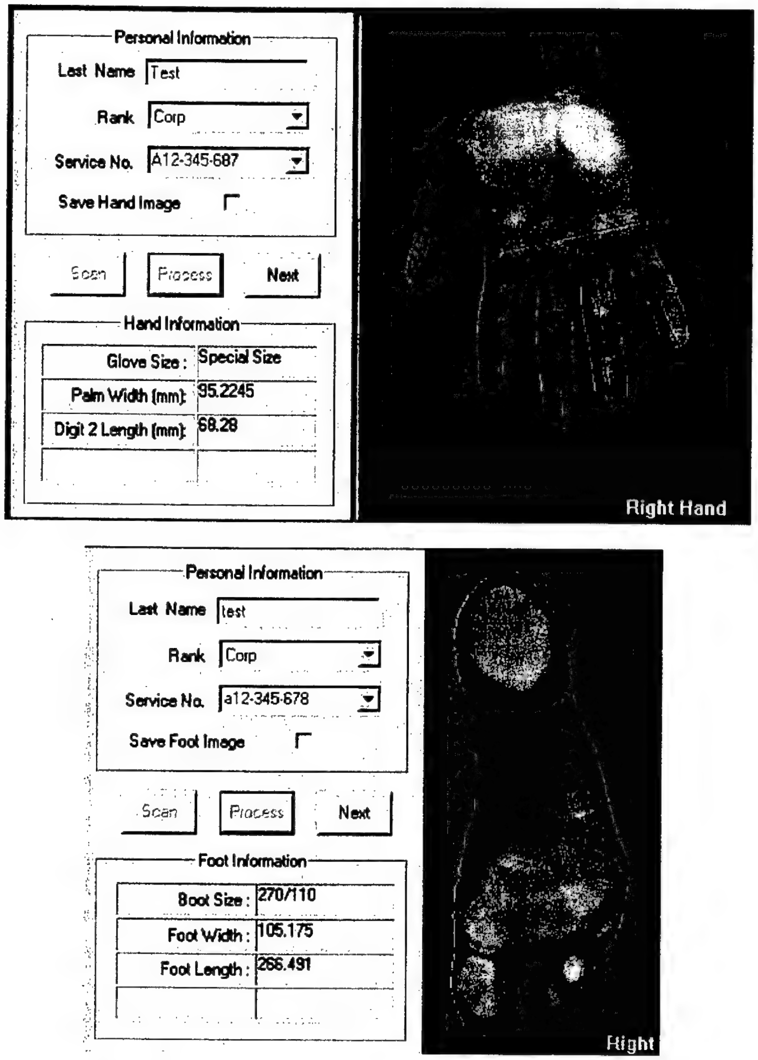

Figure 12. Processed images of the hand and foot.

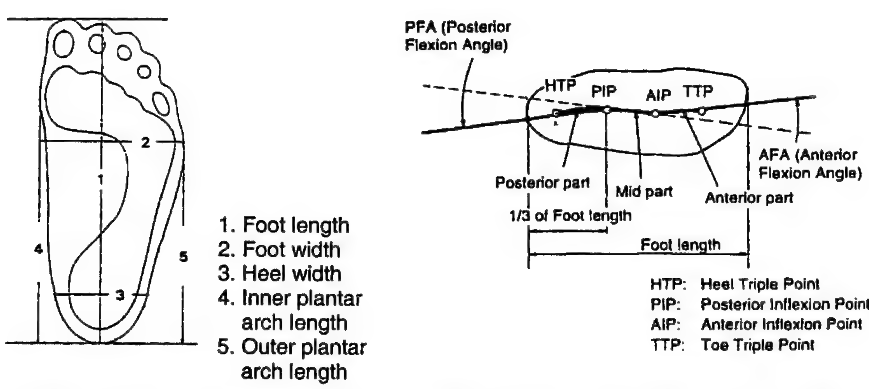

Figure 13. Foot measurement terms (Mochimaru and Makiko, 1997).

Processing capacity

Since the image processing takes about one second to extract the basic set of measurements, the cycle time of the hand and foot scanning systems is dictated by the speed of the scanner. With the current scanner, the image acquisition takes about 18 seconds to complete. If hand and foot scans were taken in series, as opposed to in parallel, the total processing time would be around 40 seconds, which is equivalent to the processing time of the body measurement. Therefore, in a production line approach, individuals could proceed from the body measurement station to the hand and foot station in an efficient manner.

Measurement performance

As in the case of the body measurement system, hand and foot measurement accuracy was assessed using data from 1997 survey of the Canadian Land Forces (Chamberland et al., 1998). Since only a limited number of hand and foot measurements were made during the survey, not all scanner measurements could be validated. Only four measurements were common for feet while only one was common for hands.

Table 7 summarises the performance of the hand and foot scanners based on data from over 300 males. Overall, correlations between 0.86 and 0.96 were found for the common measurements. The table also shows that scanner measurements were within 3 mm of the ones taken expertly by anthropometrists during the 1997 survey for most measurements. Ball of foot length measurements made from automatic landmarking were not as accurate as those derived from foot length due to the difficulty in identifying the metatarsal protrusion. As a result, the latter was used as a predictor of ball of foot length.

Table 7. *Summary performance data for hand and foot scanning*

Measurement	Correlation between survey and scanner measurements	Standard error of scanner measurement (mm)
Foot:		
Foot length	0.96	2.9
Heel breadth	0.94	1.3
Ball of foot length*	0.92	3.2
Foot breadth	0.88	2.6
Hand:		
Hand breadth	0.86	2.3
* Derived from foot length		

As a general observation, it should be noted that the optical properties of the scanners were found to produce significant bias on breadth measurements. Length measurements were unaffected. The bias was corrected to reflect the traditional measurements taken in the 1997 survey.

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Conclusions and recommendations

It is clear from the work done so far that the Intelligent Clothing and Equipment Sizing System (ICESS) can, even in its current form, improve the purchasing and distribution process. In its current standalone form, the system is capable of assigning the correct size of garment for the vast majority of users, resulting in time savings at the point of issue and a more rational use of stocks. Size data would then be fed back to the item managers who could then better forecast the purchasing requirements. This standalone mode of operating was the primary intent of the development. However, combining or integrating ICESS with the clothing and equipment suppliers and manufacturers could yield even greater benefits. For instance, the information generated by ICESS could open the door to just-in-time manufacturing, resulting in a reduction in inventory. Pushed further, this technology could be used as a basis for mass customization. In this case, clothing and equipment would be made to measure for every individual, providing the soldier exactly what is needed without alteration.

ICESS is a low-cost tool capable of capturing body size and shape in an accurate and repeatable fashion. The way in which this tool is implemented will determine the extent of its impact on the supply system. It is recommended that various alternatives be explored and that a progressive implementation plan be devised, starting with the implementation of ICESS as a standalone tool.

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List of symbols/abbreviations/acronyms/initialisms

CF	Canadian Forces
DND	Department of National Defence
DSSPM	Director of Soldier Systems Program Management
DRDC	Defence Research and Development Canada
ICESS	Intelligent Clothing and Equipment Sizing System
LF	Land Forces

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14. ABSTRACT

(U) In 1996, DCIEM initiated a preliminary study to explore the feasibility of developing a lowcost automated system capable of accurately measuring and sizing individuals. The purpose of this system is to help make the distribution of clothing and equipment more costeffective within the CF.
The development of the Intelligent Clothing and Equipment Sizing System (ICESS) has undergone three 3 phases. The first phase was an exploratory development phase focused on hardware, software architecture, and system configuration. The second phase focused on the anthropometric aspects of the systems, that is on how accurate the measurements were. In that phase, both expert anthropometrists and ICESS measured 95 females and 254 males. The third phase concentrated on the clothing sizing aspects of ICESS and the testing of traditional and non-traditional means of predicting clothing sizes from anthropometric data. This phase culminated with an assessment of the systems performance and provided the proof of concept data required to pursue implementation in the CF.
The paper summarizes work been done to date on all the three development phases. Suggestions as to its eventual implementation have also been presented.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) anthropometry, apparel, image processing, clothing sizing

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